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**Modifications to Langley 0.3-m TCT Adaptive
Wall Software for Heavy Gas Test Medium
Phase I Studies**

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MODIFICATIONS TO LANGLEY 0.3-M TCT ADAPTIVE WALL SOFTWARE FOR HEAVY GAS TEST MEDIUM

SUMMARY

The scheme for two-dimensional wall adaptation with sulfur hexafluoride (SF_6) as test gas in the NASA Langley Research Center 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) is presented. A unified version of the wall adaptation software has been developed to function in a dual gas operation mode (Nitrogen or SF_6). The feature of ideal gas calculations for Nitrogen operation is retained. For SF_6 operation, real gas properties have been computed using the departure function technique. Installation of the software on the 0.3-m TCT ModComp-A computer and preliminary validation with nitrogen operation were found to be satisfactory. Further validation and improvements to the software, if necessary, will be undertaken at a later date when the 0.3-m TCT is ready for operation with SF_6 gas.

INTRODUCTION

The Langley 0.3-m TCT¹ is a unique wind tunnel facility for testing two-dimensional airfoil models at transonic Mach numbers and flight equivalent Reynolds numbers. The high Reynolds number capability is achieved by using cryogenic nitrogen gas as the test medium. The 0.3-m TCT, since its first proof-of-the concept studies in 1976, has undergone several major changes to provide additional testing features. In its present form, the 0.3-m TCT has a 13-inch square test section with adaptive wall capability for top and bottom walls and a sophisticated side wall boundary-layer removal system. These features make possible testing of airfoil models with a greatly reduced level of wall interference.

The application of the cryogenic concept has been highly successful in simulating the much needed high Reynolds number capability at transonic speeds. Many cryogenic wind tunnels have been built in the last decade and are being used routinely to test under high Reynolds number conditions. Presently, an alternative approach of using a heavy gas in place of the cryogenic nitrogen to provide high Reynolds numbers is under consideration. The use of heavy gas permits operation under ambient temperature conditions making model design, and force and pressure measurement instrumentation simpler. Also, as demonstrated by Smelt², the power requirements will be lower.

The present heavy gas feasibility study at Langley uses sulfur hexafluoride (SF_6) which is about five times heavier than nitrogen/air. However, at a given test Mach number, the increase in Reynolds number is about two times due to lower speed of sound (30% of air) and lower viscosity (80%). The use of SF_6 also poses much less environmental concerns compared to CFCs. However, the effect of the real gas properties of SF_6 on the flow around the model and on the shock location at transonic speeds is not well known. The different value of the ratio of specific heats and other real gas effects may require corrections to be applied to the test data for valid comparison with the nitrogen test data. Therefore, to facilitate a comparative study between using cryogenic nitrogen and SF_6 , the 0.3-m TCT is being modified to operate using either gas mode. The proposed modification permits a direct tunnel-independent aerodynamic evaluation of the two different methods of generating high Reynolds numbers.

The objective of the present work is to study the aspects of using the 0.3-m TCT adaptive wall capability with the SF_6 test gas. Necessary modifications to the adaptive wall testing technique in support of the aerodynamic evaluation studies using SF_6 gas have been considered. The adaptive wall software currently in use has been developed specifically for using nitrogen gas as the testing medium. For use with SF_6 gas as the test medium, it is necessary to incorporate changes to account for the thermodynamic properties of SF_6 and other operational features. The new version of the adaptive wall control software has been developed to incorporate the following main features.

- a) Easy switching between two test media (Nitrogen & SF_6)
- b) No major changes at operator end; thus avoiding operator retraining.
- c) Retain the same program structure and add additional features to facilitate easier maintenance of the software.

This report describes the methodology used in modifying the software for the dual gas mode and provides details of the modified software developed during this first phase of the study. Limited tests were made to check the performance of the software. Final checking and changes, if needed, will be made when the tunnel is ready for operation with SF_6 gas.

Nomenclature

- $A_{0,4}$ Constants in expression for constant-pressure ideal heat capacity (Eqn. 2)
- a Speed of sound (meter/second)

$a_{2,5}$	Constants in equation of state (Eqn. 1)
b	Constant in equation of state (Eqn. 1)
$h_{2,5}$	Constants in equation of state (Eqn. 1)
C_p	Constant-Pressure heat capacity
C_p^o	Constant-Pressure ideal heat capacity
C_v	Constant-Volume heat capacity
C_v^o	Constant-Volume ideal heat capacity
$c_{2,5}$	Constants in equation of state (Eqn. 1)
H	Enthalpy (Joule/kmole)
k	Constant in equation of state (Eqn. 1)
M	Mach number
N_2	Nitrogen
P	Pressure (Newton/meter ²)
R	Universal gas constant (= 8314.34 Joule/(kmole Kelvin))
S	Entropy (Joule/(kmole Kelvin))
SF_6	Sulfur hexafluoride
T	Temperature (Kelvin)
T_c	Constant in equation of state (Eqn. 1)
U	Velocity (meter/second)
V	Volume (meter ³ /kmole)
W	Molecular weight
Z	Compressibility factor
γ	Ratio of specific heats (C_p/C_v)
ρ	Density (kg/m ³)

Subscripts

t	Stagnation conditions
v	Volume
l	Static conditions after isentropic expansion

0.3-m TCT Adaptive Wall Test Section

The 0.3-m TCT adaptive wall test section (fig. 1) uses a flexible wall concept for wall adaptation. It has rigid side walls and flexible stainless steel plates for the ceiling and the floor. The test

section has a square cross section with a nominal height of 0.33m (13.0 in.) with the flexible walls set to a flat shape. The flexible plates, 1.82m (71.7 in.) long, are anchored at the upstream end and are free to move longitudinally in a sliding joint at the downstream end.

The wall shapes are controlled by stepper motor operated jacks positioned at twenty-one locations on the ceiling and floor. The wall positions are monitored by linearly variable differential transducers (LVDT) located at each jack station. The wall positions are referenced to the undeformed straight wall shape. In addition to the wall shapes, the wall streamlining algorithm requires the fluid velocity distribution along the wall. This is calculated from measured wall pressures at the jack locations from static pressure orifices. The reference test Mach number is determined by a static pressure measurement near the upstream anchored end of the flexible plates. This station is 0.8m (31.25 in.) upstream of the model mounting turntable center.

Wall Adaptation Method

Wall adaptation is the process of adjusting the test section wall shapes to nearly free air streamline shapes. Modern methods developed in the last decade are based on the iterative concept proposed independently by Ferri and Baronty³ and Sears⁴. The iterative concept treats the flow over the model in two parts; the real wind tunnel flow inside the test section and an imaginary flow extending to infinity outside the test section walls. For a test section with flexible walls for the boundaries, the matching of the flow conditions at the boundaries leads to wall shapes close to free air streamline shapes. This concept of streamlining was first introduced by Goodyer⁵ to define the streamlined conditions for a solid flexible wall wind tunnel. The wind tunnel measurements give the flow velocity and direction at the boundaries. One of these quantities along with the boundary condition at infinity is sufficient to calculate the imaginary flow. The other quantity serves as a compatibility check. Iterative calculation of the real and imaginary flows leads to identical flow conditions at the interface boundary.

There are two approaches to applying the iterative concept of adapting the walls. The first method, known as the interface discontinuity method, is particularly suitable to two-dimensional airfoil testing. The interface discontinuity method treats the imaginary flow outside the test section ceiling and floor separately. The calculated wall deflections for each wall are then modified by adding a portion of the deflection for the opposite wall to represent the coupling effects. The second approach⁶ considers the coupling effects by using the Cauchy integral formula and eliminates the need for separate calculation of the imaginary flows for the ceiling and floor.

Further, the concept can be extended to three dimensional test section using Green's theorem.

For the 0.3-m TCT, the interface discontinuity approach has largely been used. A limited study⁷ using the second approach has been made. The purpose of this study was to demonstrate the concept of making simultaneous calculation of wall adaptation and residual interference, and also to identify some of the shortcomings⁸ of the wall adaptation method (WAS-1) then in use at the 0.3-m TCT.

0.3-m TCT Adaptive Wall Software & Present Status

The 0.3-m TCT adaptive wall software has been developed over a number of years by several authors. The software function can be broadly divided into two categories. The first category relates to the control of the flexwall hardware, measurement of wall pressures and positions, and associated safety features. This portion of the software function will not be affected by the heavy gas operation. The second category, critical to the adaptive wall function, is the algorithm used to calculate the wall shapes.

As mentioned earlier, the algorithm used in the 0.3-m TCT is based on the interface discontinuity approach. The related studies were primarily developed at the University of Southampton, England and adapted to the 0.3-m TCT at various stages. Within the concept of interface discontinuity, different approaches to calculate the imaginary flow are possible. Reference 9 gives the details of a predictive strategy known as WAS-1, first developed at the University of Southampton. The WAS-1 method was implemented later at the 0.3-m TCT and has been used in a number of airfoil tests. Reference 10 which describes in detail the 0.3-m TCT Wall adjustment strategy software, incorporates the WAS-1 method.

Despite its wide use in a number of airfoil tests, the experience at Langley in using the WAS-1 was not encouraging⁸. Hence, during late 1988, the WAS-1 method was replaced with a different method known as IFLEX. This major revision is not documented and should be considered as an integral part of reference 10.

Reference 11 gives the details of the IFLEX method and a program in HP Basic language. The IFLEX method creates an imaginary semi-infinite flowfield which has a streamline originating at infinity and has the same shape as the flexible wall. The method represents (fig. 3) the wall shapes by a distribution of sources and sinks on a line corresponding to the straight wall shapes.

The sources/sink strengths are determined by the local wall slopes. The difference between the measured wall pressures and the imaginary flowfield field solution is a measure of new wall movements required to adjust the walls to streamline shapes. The procedure is again iterative. Since the top and bottom wall shapes are generally different, separate calculations are made for each wall.

The IFLEX approach overcomes the shortcomings of the original WAS-I method. Since its installation, the streamlining performance has been found to be satisfactory for the airfoils tested. However, with a new computer operating system installed during 1991, difficulties were encountered with convergence of the wall contours. This necessitated a complete check-out of the software before modifications for the SF_6 operation could be incorporated. Details of the preliminary check-out program are given in Appendix A. The problem was found to be unrelated to IFLEX performance but required changes to the code to work satisfactorily with the new operating system.

Wall Adaptation for Sulfur Hexafluoride Test Medium

The principle of wall adaptation as used in the IFLEX approach is essentially based on incompressible flow theory along with the Prandtl-Glauert rule to take into account the effect of compressibility. This assumption implies that the flow conditions at the wall be subsonic whereas the flow over the model can still have regions of supersonic flows and shock waves. This condition is satisfied for most of the transonic testing conditions encountered in the tunnel.

The requirement of subsonic flow conditions implies that the shape of the free-air streamline shapes are independent of the gas properties for a given test Mach number. Therefore, to first order, the wall shapes in the fully adapted conditions must be the same for both the nitrogen and sulfur hexafluoride operation. However, the approach to the final adapted conditions will be different because of the different thermodynamic properties. For a given wall shape and free stream Mach number, the measured wall pressures will be different for nitrogen and sulfur hexafluoride. Correspondingly, the calculated speed of sound and the fluid velocities at the walls will also be different. However, the values of the pressure coefficients remain the same in both cases. This feature has been utilized to simulate SF_6 with nitrogen operation. This option will be helpful during final validation tests.

Results and Discussion

Properties of Sulfur Hexafluoride

The change in wall adaptation calculation for sulfur hexafluoride gas arises from the fact that the ratio of specific heats is about 1.1 compared to 1.4 for the nitrogen gas. The present adaptive wall software for nitrogen operation uses a constant value of 1.4 for all test conditions. This approximation is adequate since nitrogen behaves like a perfect gas over the operating conditions of interest.

For SF_6 operation, the following three options are possible for representing the real gas effects in wall adaptation calculations.

- a. Use a specified constant value of γ_{SF_6}
- b. Use value of γ_{SF_6} based on stagnation conditions.
- c. Perform complete real gas calculations to calculate the thermodynamic properties.

In contrast to nitrogen, the thermodynamic behavior of SF_6 departs from ideal gas even at fairly low pressures. Hence the calculation of thermodynamic properties require solution of the equation of state and ideal heat capacity equation¹²:

$$P = \frac{RT}{(V - b)} \sum_{i=2}^{i=5} \frac{a_i + b_i T + c_i \exp(-kT/T_c)}{(V - b)^i} \quad (1)$$

$$C_p^\circ = A_0 + A_1 T + A_2 T^2 + A_3 T^3 + A_4 T^{-2} \quad (2)$$

Reference 13 gives in detail the solution of the above equations and also the procedure to calculate properties after isentropic expansion using the departure function technique. In the present calculations, the method of reference 13 has been used. Appendix B gives a summary of the results obtained in reference 13.

Figures 4a-e show the change in thermodynamic properties of SF_6 over the range of pressures (1-8 atm.) and temperatures (275-350K) of interest to testing in the 0.3-m TCT. The ratio of specific heat, γ , increases from about 1.1 at 1 atmospheric pressure to about 1.13 at 6 atmospheres under ambient temperature conditions. Hence, it would be difficult to fix a priori a constant value for the ratio of specific heats to simplify adaptive wall calculations. The compressibility effects increase rapidly with increase in pressure (fig. 4b). With increase in pressure, the acoustic speed (fig. 4c) decreases at a given temperature. Hence, for a given Mach number the fluid velocity will be lower at higher pressures than at lower pressures. The decrease in density with increase in temperature is shown in fig. 4d. The specific heat at constant pressure (fig. 4e) shows non-linear changes for higher pressures and temperatures below about 275 K. Hence it appears that to avoid rapid variations in the properties, it is advisable to work at a stagnation temperature of about 300K or higher.

In addition to these features, the isentropic expansion causes a drop in pressure and temperature. The determination of the Mach number after isentropic expansion from stagnation conditions requires solution for the entropy equation along with the equation of state and constant pressure ideal heat capacity (Appendix B). As mentioned earlier, reference 13 gives a computer program to calculate the isentropic expansion. Figure 5 shows the Mach number after isentropic expansion from an initial stagnation condition of 8 atmospheres pressure and 300K temperature. The Mach numbers obtained from real gas calculations are higher than the values using a constant value of γ based stagnation conditions. The differences are smaller at lower Mach numbers. The use of heavy gas though requires higher pressures to increase the Reynolds numbers. To account properly for departure from ideal conditions, it is necessary to retain real gas calculations in the wall adaptation process in the initial studies.

Simplified calculations based on a fixed value of γ may be possible after some experience is gained. While such a simplified calculation may be adequate from the wall adaptation process, the residual errors in the Mach number may be of uncertain magnitude if different types of calculation are performed for tunnel measurements (ModComp-B) and wall adaptation (ModComp-A). Hence, in the present work, complete real gas calculations based on the departure function technique have been implemented. Further modifications to provide an option for using a fixed value of γ can be incorporated.

Program Implementation

A Fortran program suitable for implementation on the 0.3-m TCT ModComp-A computer was developed based on the method described in reference 13. The program was validated on a HP-workstation before installing on the Modcomp computer and integrating with the adaptive wall software. The original version of the program presented in reference 13 uses double precision calculation to solve the transcendental equations. It was felt that the double precision calculation may not be required in a real time environment. Further, double precision is not compatible with the remaining calculations, performed using single precision.

Table 1a compares the results of single and double precision calculations on the 0.3-m TCT ModComp 16-bit computer for a high pressure test case. The difference between the two results is not significant, implying that the single precision calculation is adequate. Table 1b and 1c show examples of single precision calculations for stagnation pressures of 0.6 and 6 atmospheres respectively. The results are also compared with results obtained on a HP workstation for validation purposes. However, using single precision calculation requires the convergence limits to be altered suitably. A typical value of convergence used was 10^{-6} for the ratio of the change in parameter value to the initial value between two iterations.

Program Integration:

The real gas program discussed above was integrated with the adaptive wall software described in reference 10. The program integration required several changes to many subroutines so that the integrated software works in the dual gas mode. Appendix D gives a summary of the various programs and subroutines in the modified software. A source listing of the modified and new programs added is presented in a separate report. The program is now presently installed on the following partitions of 0.3-m TCT ModComp-A computer.

- | | | |
|-----------------|-----|---------------|
| a. Source files | ... | Partition ESL |
| b. Object files | ... | Partition EUL |
| c. Load files | ... | Partition ELM |

The start-up and execution procedures remain the same except the load module is assigned to the new partition by command //ASS LM ELM. No changes have been made in the OAP system.

In the present version, the software developed has the following features.

- a. Functions in both the nitrogen and SF_6 modes.
- b. Choice of the mode, either nitrogen or SF_6 , is made from the digital control panel. The values of the parameter IANAL are incremented by 10 to represent SF_6 mode of operation (Appendix C)
- c. All the previous features of the control software have been retained. Hence, procedures at the operator level remain unaffected.
- d. Automatic or manual selection of scaling factors (Appendix C)
- e. Appropriate message, whether in the nitrogen or SF_6 mode, is displayed on the terminal at various stages of program execution during testing.

Appendix C gives a summary of the various settings on the digital control panel for the present version of the software. To facilitate installation and checking the various functions of the program, a simulation routine has been added. The function of this subroutine is to convert the pressures measured during operation with nitrogen to equivalent pressures with SF_6 operation. This will be helpful in initial checking and can be retained, if necessary, as an additional feature of the software. Suitable changes are necessary after final validation to retain or delete this feature.

Validation Tests

The integrated program was successfully installed and wind-off checks were made to ensure the execution of the software in the modified version. A limited number of wind-on checks were made to check execution of the flexwall data acquisition and ensure satisfactory execution in the nitrogen mode. One of the tests involved a complete wall streamlining cycle with a space shuttle model. Though the two-dimensional streamlining procedure for a three-dimensional model may not be exact, the test was mainly meant to prove the functioning of the software in the nitrogen mode. These initial tests have been useful and have saved considerable development work that would have been required later with the heavy gas. Final wind-on proof tests with the SF_6 gas

will be conducted later when the 0.3-m TCT is ready for operation with SF_6 gas. In the present form, the real gas calculation portion of the software has optional outputs which will be useful in debugging the program. However, the optional printing may slow down the process and will be suppressed in the final version.

Appendix E gives a listing of the program used on the HP workstation to calculate the properties of SF_6 gas and isentropic expansion. The program can be executed interactively and has provisions for real gas calculations or for using a specified value of the ratio of specific heats. This option can be installed on the 0.3-m TCT ModComp computer, if found necessary, after final validation tests.

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TABLE 1a

COMPARISON OF SINGLE & DOUBLE PRECISION CALCULATIONS FOR SF6
 PROPERTIES ON MODCOMP-A (STAGNATION PRESSURE = 6.0 ATM.)

	MODCOMP-A (REAL*4)	MODCOMP-A (REAL*8)
STAGNATION CONDITIONS =====		
P, NEWTON/M ²	607000.000000	607000.000000
T, TEMPERATURE, K	305.000000	305.000000
V, VOLUME M ³ /KMOLE	3.905272	3.905273
DENSITY, KG/M ³	37.399185	37.399183
Z, COMPRESSIBILITY FACTOR	0.934786	0.934786
CP0, CONS PR IDEAL HEAT CAP. J/KMOLE,K =	98714.062500	98714.029078
CVO, CONS VOL IDEAL HEAT CAP. J/KMOLE,K =	90399.718750	90399.689078
CP-CV, J/KMOLE,K	11429.773437	11429.783681
CP, CONS PR HEAT CAP. J/KMOLE,K	104350.812500	104350.787244
CV, CONS VOL HEAT CAP. J/KMOLE,K	92921.031250	92921.003563
GAMMA (RATIO CP/CV)	1.123005	1.123005
SOUND SPEED, METERS/SEC	130.293091	130.293218
ISENTROPIC EXPANSION: =====		
P, NEWTON/M ²	420000.000000	420000.000000
T, TEMPERATURE, K	294.678345	294.678423
V, VOLUME M ³ /KMOLE	5.540188	5.540190
DENSITY, KG/M ³	26.362640	26.362633
Z, COMPRESSIBILITY FACTOR	0.949725	0.949725
CP0, CONS PR IDEAL HEAT CAP. J/KMOLE,K =	96314.781250	96314.822471
CVO, CONS VOL IDEAL HEAT CAP. J/KMOLE,K =	88000.437500	88000.482471
CP-CV, J/KMOLE,K	10666.144531	10666.147160
CP, CONS PR HEAT CAP. J/KMOLE,K	100819.187500	100819.204486
CV, CONS VOL HEAT CAP. J/KMOLE,K	90153.031250	90153.057325
GAMMA (RATIO CP/CV)	1.118311	1.118312
SOUND SPEED, METERS/SEC	129.938538	129.938625
VELOCITY (M/SEC)	108.851898	108.851251
MACH NUMBER	0.837718	0.837713
TEST-SECTION MASS FLOW (KGS/SEC)	312.788940	312.787014
DYNAMIC PRESSURE (N/M ²)	156181.937500	156180.082255
REYNOLDS NO./METER	0.183099E+09	0.183098E+09
RATIO PSTATIC/PTOTAL	0.691927	0.691928
RATIO PSTATIC/PTOTAL	0.966158	0.966159
RATIO RHO-STATIC/RHO-TOTAL	0.704899	0.704899
RATIO DYN-PR/PTOTAL	0.257301	0.257298

TABLE 1b

COMPARISON OF SINGLE PRECISION CALCULATIONS FOR SF6 PROPERTIES
(STAGNATION PRESSURE = 0.6 ATM.)

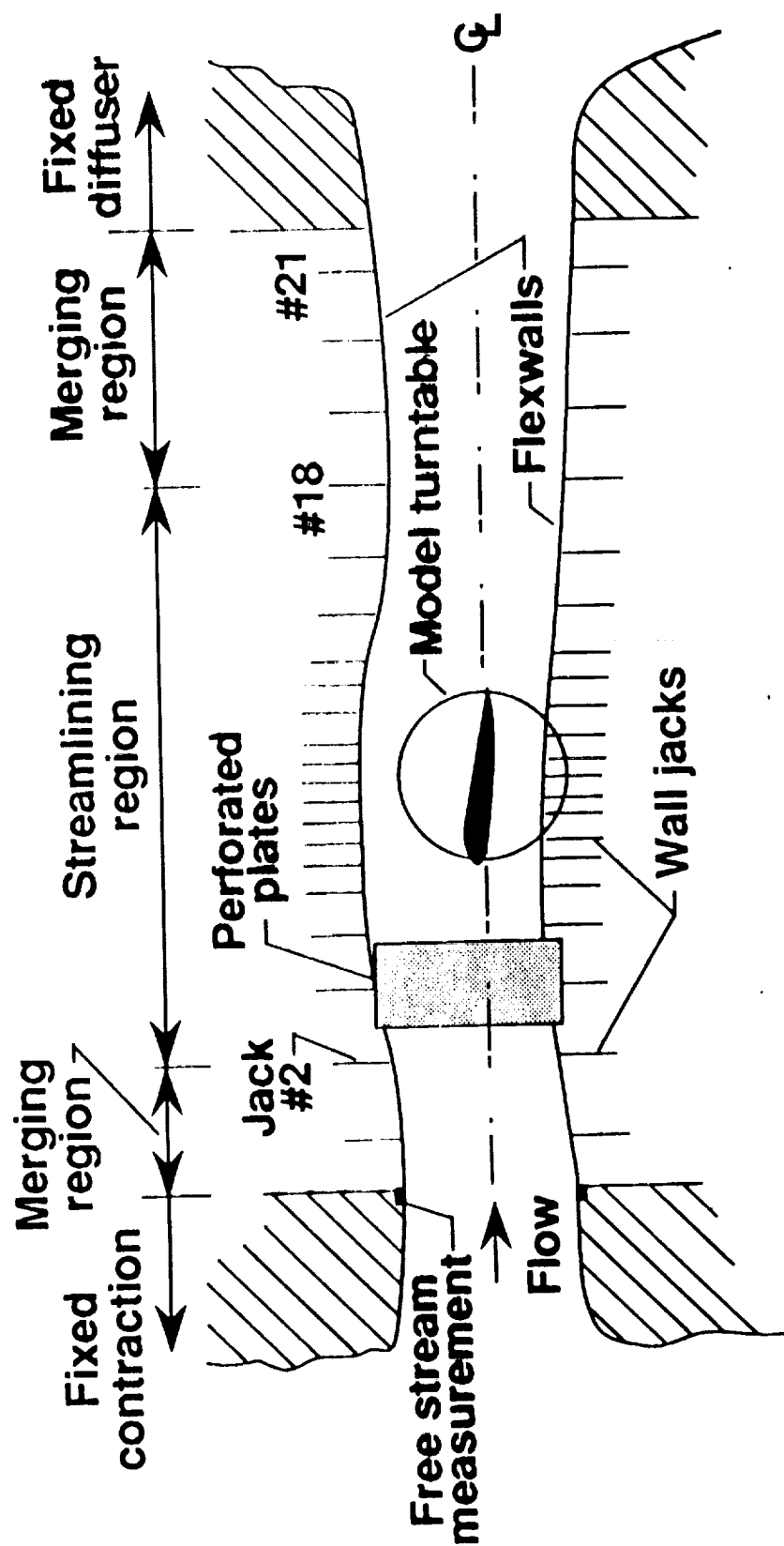
	MODCOMP-A (16 bit)	HP-345 (32 Bit)
STAGNATION CONDITIONS =====		
P, NEWTON/M ²	= 60700.000000	60700.000000
T, TEMPERATURE, K	= 305.000000	305.000000
V, VOLUME M ³ /KMOLE	= 41.517105	41.517113
DENSITY, KG/M ³	= 3.517923	3.517923
Z, COMPRESSIBILITY FACTOR	= 0.993775	0.993775
CP0, CONS PR IDEAL HEAT CAP. J/KMOLE,K =	98714.062500	98714.039000
CVO, CONS VOL IDEAL HEAT CAP. J/KMOLE,K =	90399.718750	90399.703000
CP-CV, J/KMOLE,K	= 8569.808594	8569.810500
CP, CONS PR HEAT CAP. J/KMOLE,K	= 99208.937500	99208.937000
CV, CONS VOL HEAT CAP. J/KMOLE,K	= 90639.125000	90639.125000
GAMMA (RATIO CP/CV)	= 1.094549	1.094549
SOUND SPEED, METERS/SEC	= 136.995361	136.995460
ISENTROPIC EXPANSION: =====		
P, NEWTON/M ²	= 35000.000000	35000.000000
T, TEMPERATURE, K	= 290.833618	290.833670
V, VOLUME M ³ /KMOLE	= 68.796326	68.796341
DENSITY, KG/M ³	= 2.122991	2.122991
Z, COMPRESSIBILITY FACTOR	= 0.995774	0.995774
CP0, CONS PR IDEAL HEAT CAP. J/KMOLE,K =	95394.500000	95394.546000
CVO, CONS VOL IDEAL HEAT CAP. J/KMOLE,K =	87080.156250	87080.203000
CP-CV, J/KMOLE,K	= 8491.566406	8491.565400
CP, CONS PR HEAT CAP. J/KMOLE,K	= 95758.843750	95758.906000
CV, CONS VOL HEAT CAP. J/KMOLE,K	= 87267.281250	87267.343000
GAMMA (RATIO CP/CV)	= 1.097305	1.097305
SOUND SPEED, METERS/SEC	= 134.214905	134.214980
VELOCITY (M/SEC)	= 136.300598	136.300330
MACH NUMBER	= 1.015540	1.015538
TEST-SECTION MASS FLOW (KGS/SEC)	= 31.540771	31.540716
DYNAMIC PRESSURE (N/M ²)	= 19720.304687	19720.232000
REYNOLDS NO./METER	= 0.187199E+08	0.187199E+08
RATIO PSTATIC/PTOTAL	= 0.576606	0.576606
RATIO PSTATIC/PTOTAL	= 0.953553	0.953553
RATIO RHO-STATIC/RHO TOTAL	= 0.603478	0.603478
RATIO DYN-PR/PTOTAL	= 0.324881	0.324880

TABLE 1c

COMPARISON OF SINGLE PRECISION CALCULATIONS FOR SF6 PROPERTIES
(STAGNATION PRESSURE = 6.0 ATM.)

	MODCOMP-A (16 Bit)	HP-345 (32 Bit)
STAGNATION CONDITIONS =====		
P, NEWTON/M ²	607000.000000	607000.000000
T, TEMPERATURE, K	305.000000	305.000000
V, VOLUME M ³ /KMOLE	3.905272	3.905273
DENSITY, KG/M ³	37.399185	37.399178
Z, COMPRESSIBILITY FACTOR	0.934786	0.934787
CP0, CONS PR IDEAL HEAT CAP. J/KMOLE,K =	98714.062500	98714.039000
CVO, CONS VOL IDEAL HEAT CAP. J/KMOLE,K =	90399.718750	90399.703000
CP-CV, J/KMOLE,K	11429.773437	11429.782000
CP, CONS PR HEAT CAP. J/KMOLE,K	104350.812500	104350.790000
CV, CONS VOL HEAT CAP. J/KMOLE,K	92921.031250	92921.015000
GAMMA (RATIO CP/CV)	1.123005	1.123005
SOUND SPEED, METERS/SEC	130.293091	130.293220
ISENTROPIC EXPANSION: =====		
P, NEWTON/M ²	420000.000000	420000.000000
T, TEMPERATURE, K	294.678345	294.678300
V, VOLUME M ³ /KMOLE	5.540188	5.540190
DENSITY, KG/M ³	26.362640	26.362633
Z, COMPRESSIBILITY FACTOR	0.949725	0.949725
CP0, CONS PR IDEAL HEAT CAP. J/KMOLE,K =	96314.781250	96314.820000
CVO, CONS VOL IDEAL HEAT CAP. J/KMOLE,K =	88000.437500	88000.484000
CP-CV, J/KMOLE,K	10666.144531	10666.148000
CP, CONS PR HEAT CAP. J/KMOLE,K	100819.187500	100819.210000
CV, CONS VOL HEAT CAP. J/KMOLE,K	90153.031250	90153.062000
GAMMA (RATIO CP/CV)	1.118311	1.118312
SOUND SPEED, METERS/SEC	129.938538	129.938610
VELOCITY (M/SEC)	108.851898	108.851430
MACH NUMBER	0.837718	0.837714
TEST SECTION MASS FLOW (KGS/SEC)	312.788940	312.787500
DYNAMIC PRESSURE (N/M ²)	156181.937500	156180.590000
REYNOLDS NO./METER	0.183099E+09	0.183098E+09
RATIO PSTATIC/PTOTAL	0.691927	0.691927
RATIO PSTATIC/PTOTAL	0.966158	0.966159
RATIO RHO-STATIC/RHO-TOTAL	0.704899	0.704899
RATIO DYN-PR/PTOTAL	0.257301	0.257299

SCHEMATIC OF 0.3-m TCT ADAPTIVE WALL TEST SECTION



(not to scale)

Fig. 1: 0.3-m Transonic Cryogenic Tunnel Adaptive Wall Test Section

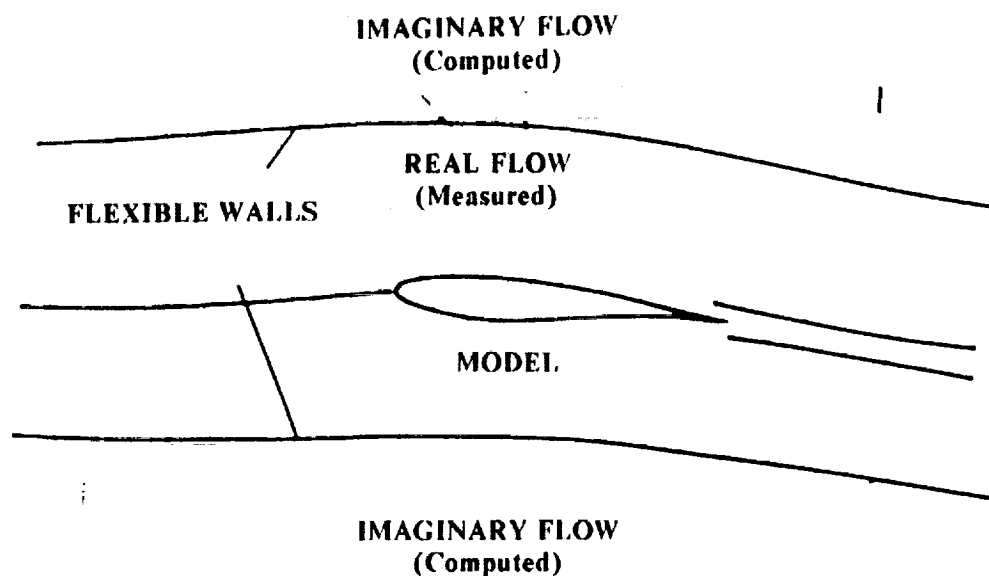


Fig. 2: Real and Imaginary Flow Fields in Wall Adaptation.

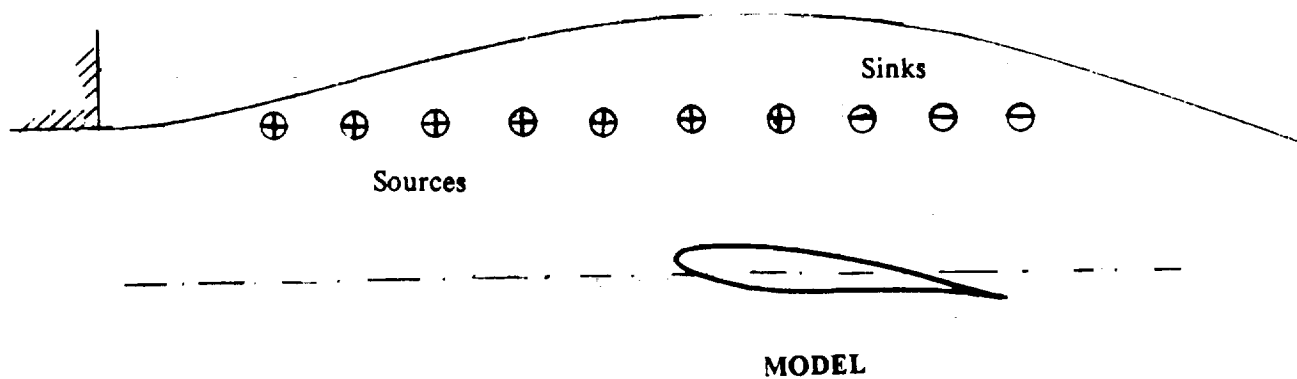


Fig. 3: Distribution of Sources and Sinks in IFLEX Method.

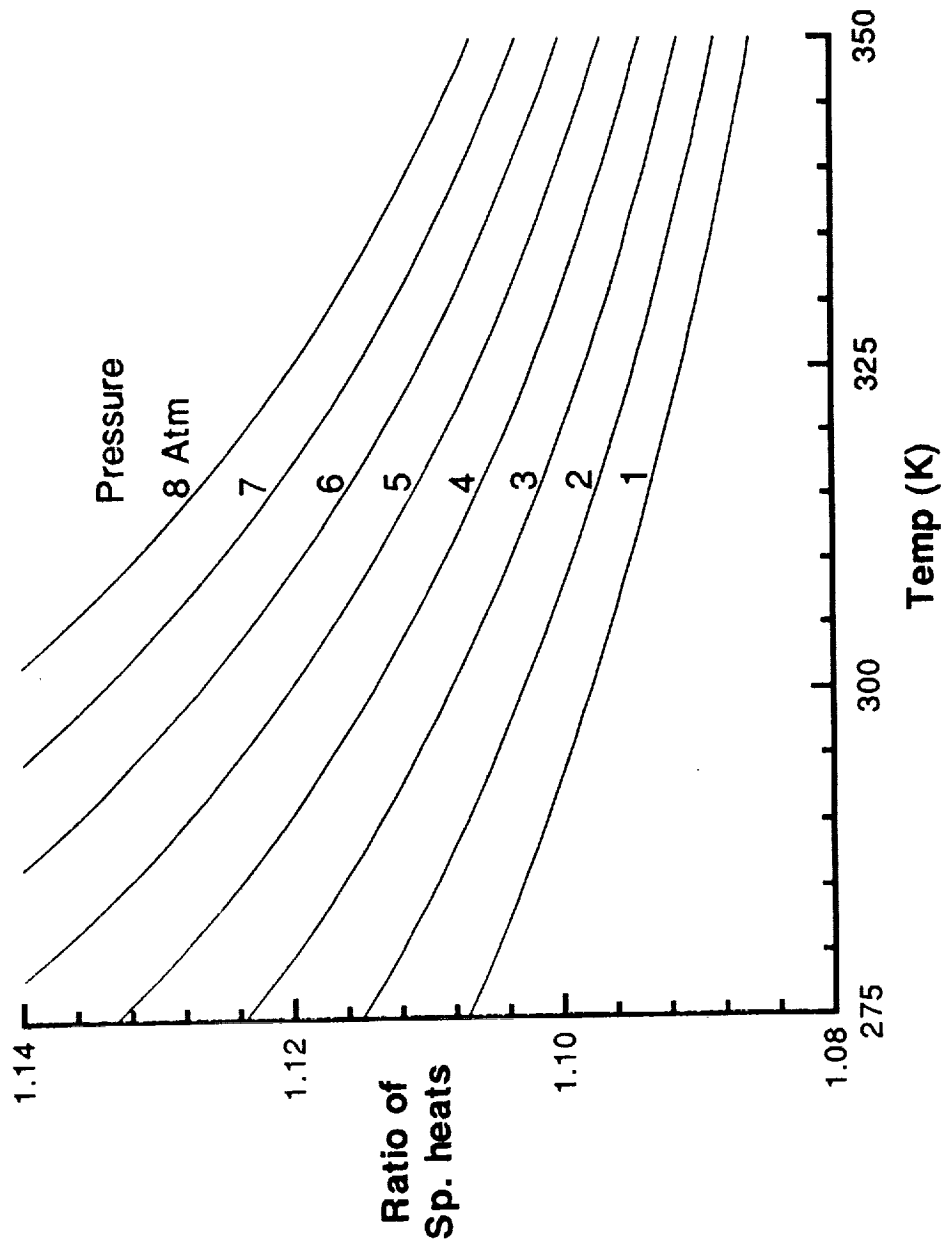


Fig. 4a: Variation of Ratio of Specific Heats for SF_6 with Pressure and Temperature.

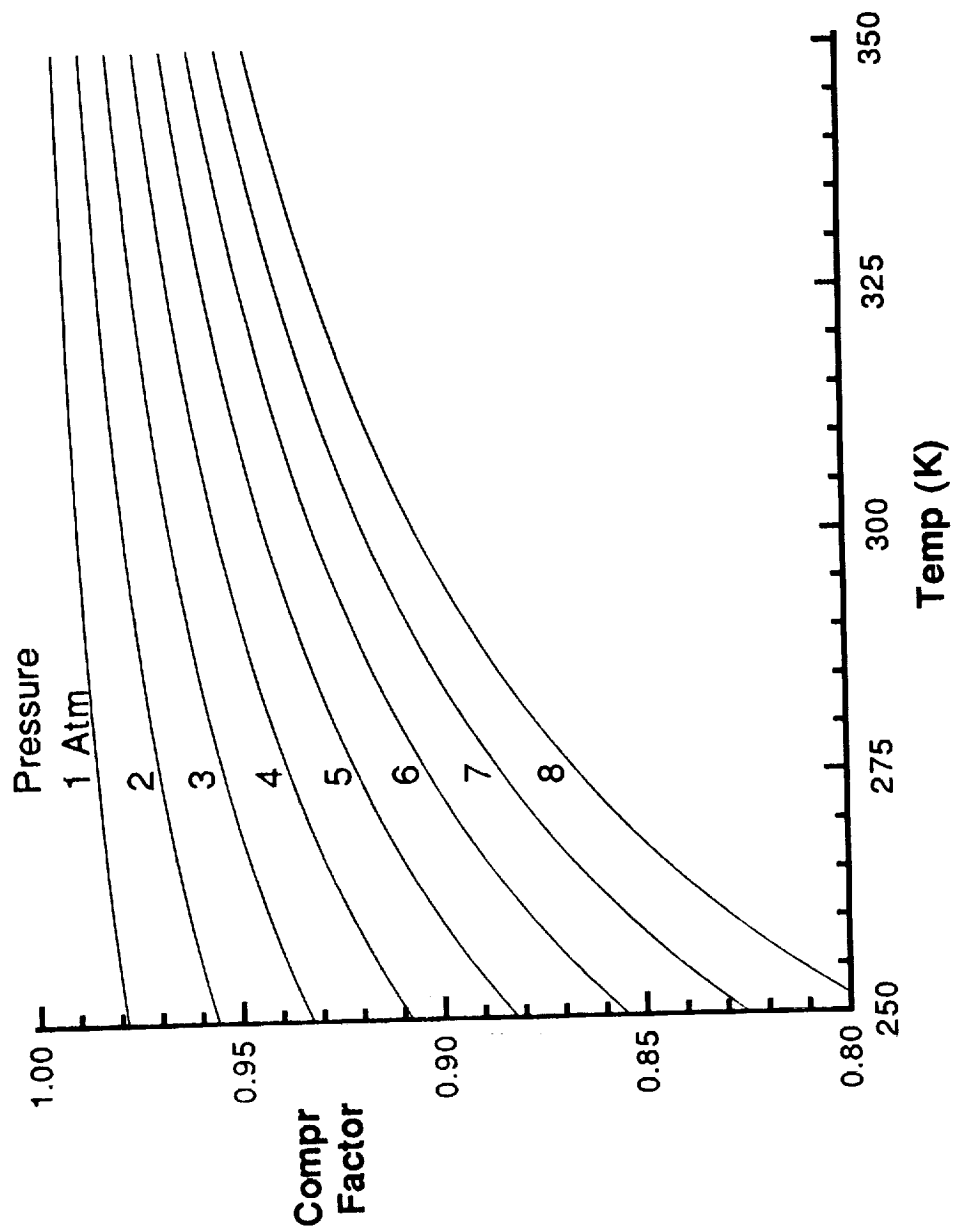


Fig. 4b: Variation of Compressibility Factor for SF₆ with Pressure and Temperature.

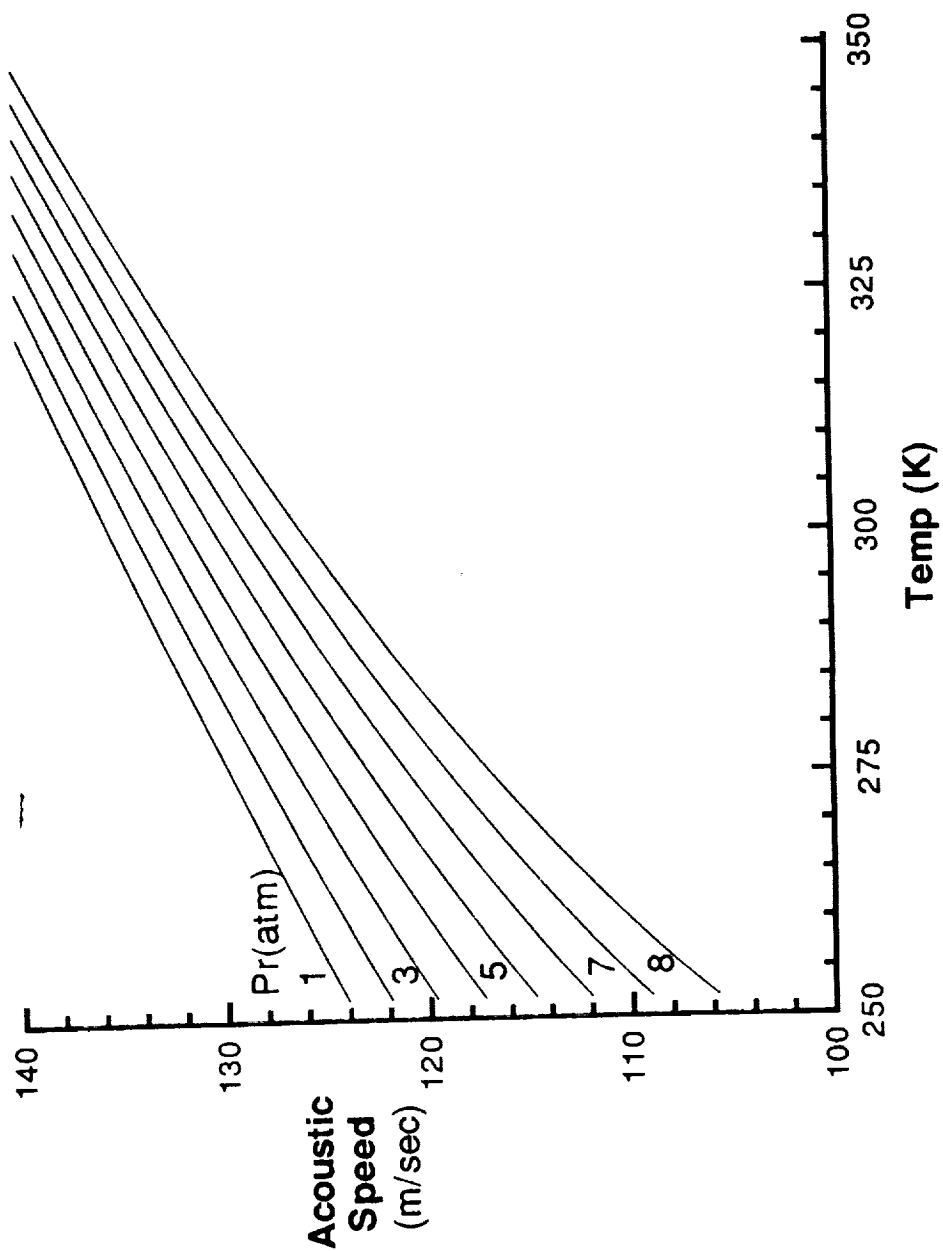


Fig. 4c: Variation of Acoustic Speed for SF₆ with Pressure and Temperature.

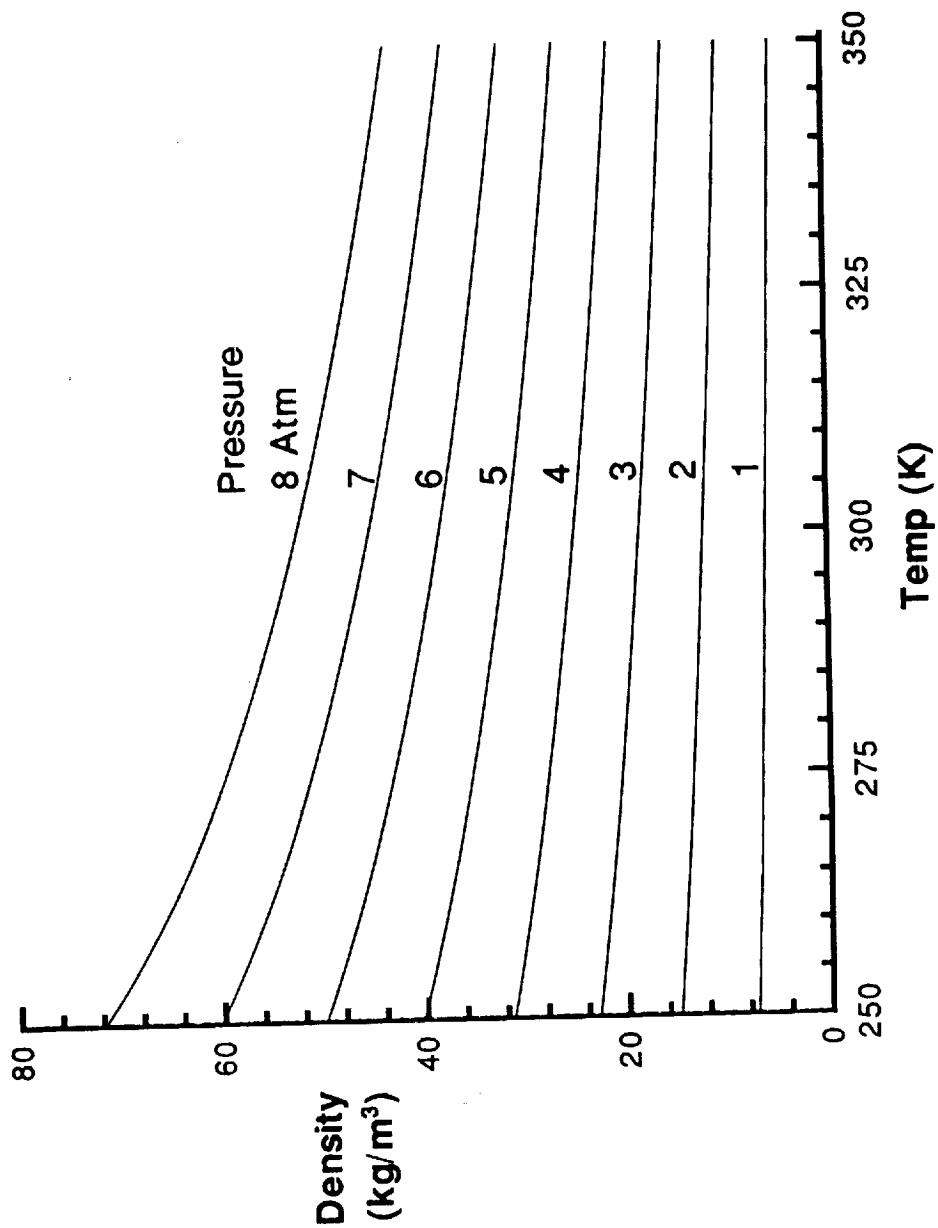


Fig. 4d: Variation of Density for SF₆ with Pressure and Temperature.

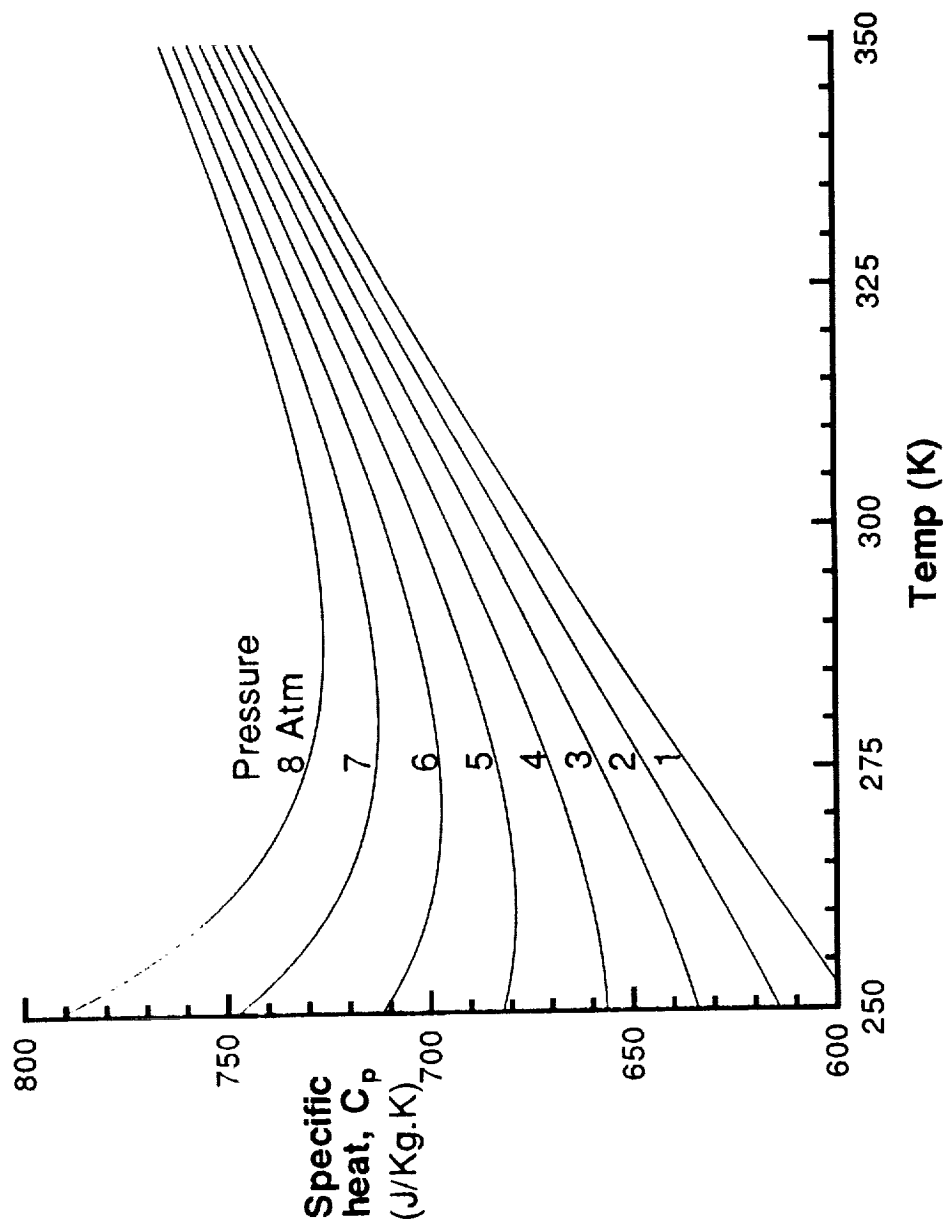


Fig. 4e: Variation of Specific Heat (C_p) for SF_6 with Pressure and Temperature.

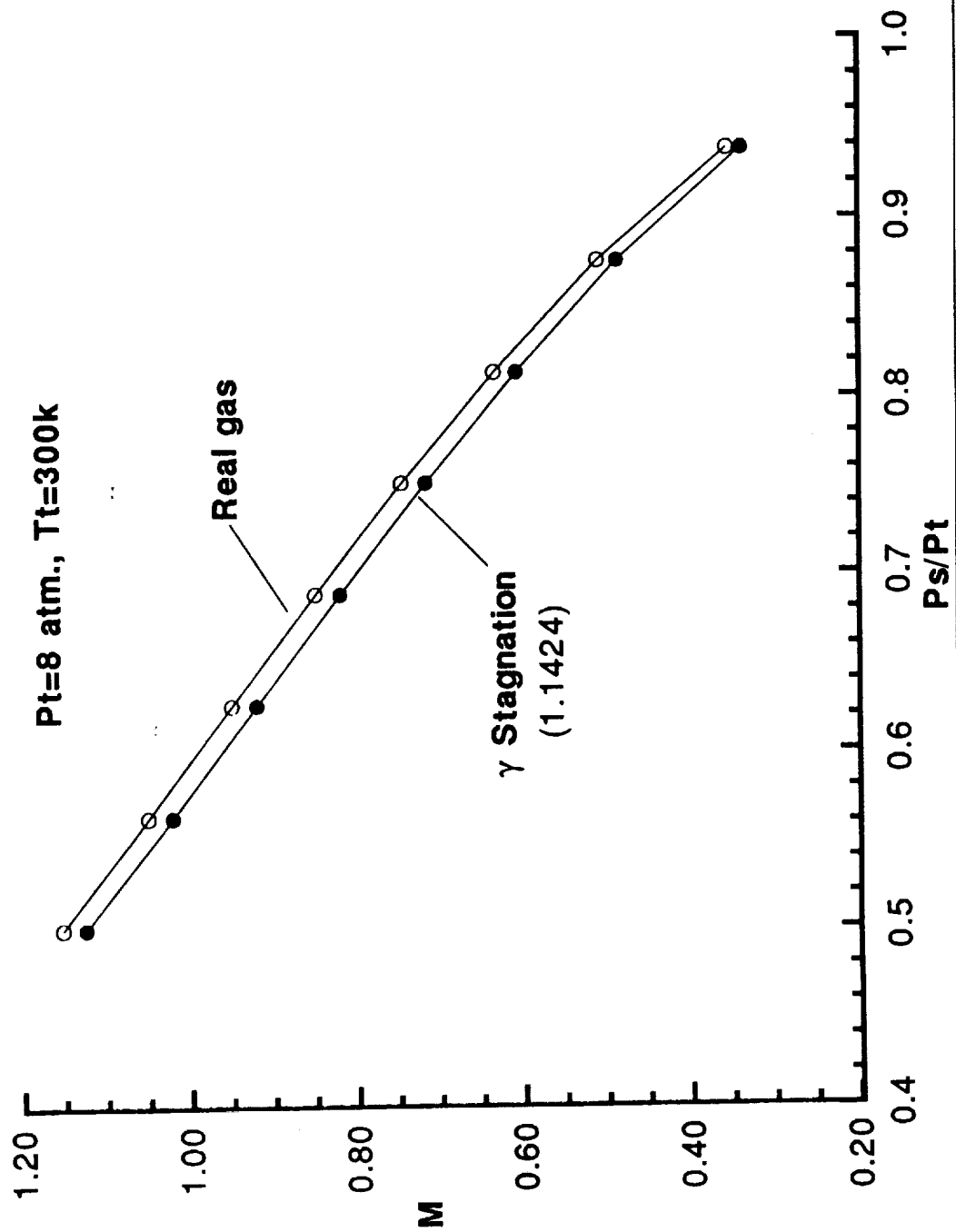


Fig. 5: Comparison of Mach number after Isentropic Expansion Using Real Gas and Stagnation value of Ratio of Specific Heats.

APPENDIX A

Preliminary Check-Out of the 0.3-m TCT Adaptive Wall System

The purpose of this check-out program was to ensure that the 0.3-m TCT adaptive wall system is functioning satisfactorily before the changes for sulfur hexafluoride operation can be implemented. This effort was necessary in view of the several changes to both the tunnel hardware and software systems in the last two years. Initial operation by the 0.3-m TCT staff on a check-out model proved unsuccessful in obtaining a successful operation of the adaptive walls and convergence of wall shapes. Following this effort, the check-out program was initiated using the 13-inch chord NACA 0012 airfoil model.

The check-out program consisted of the following:

- a) Primary measurements
 - Tunnel total pressure
 - Tunnel static pressure
 - Tunnel reference pressures
- b) Adaptive wall hardware:
 - Wall alignment, LVDT calibrations
 - Wall pressure measurements and instrumentation
- c) Control software

The check-outs for items a-b, and rectifying the observed problems, greatly helped the adaptive walls to perform in a predictable manner. Most of the problems were not of a type as to cause adverse effects on the wall adaptation process. However, they needed rectification in order to achieve the desired test accuracy and trouble free wall movements in a production testing environment. One of the major source of errors which affected blockage corrections was a leakage in the total pressure measurement tubing. The wall pressure measurements were also checked using both tunnel static and vacuum as reference pressures.

After these changes, it was noted that the walls moved correctly in the first iteration, but never seemed to converge in subsequent iterations. The solutions for wall shapes showed continuous driving of the walls towards free jet conditions. It was difficult to attribute this behavior to any known past trends or experience. No obvious errors or doubts about measurement systems were present at this stage.

More detailed off-line checks of the wall adjustment software on a HP workstation showed that the wall shape solutions were satisfactory and the interference levels low enough to be acceptable. This enigma was resolved by tracing the cause of the error to a limitation of the new operating system recently installed on the ModComp computer in the 0.3-m TCT. The new system interpreted multiplication of an integer constant and a real variable differently in the subroutine IFLEX which calculates new wall shapes for each iteration. This limitation resulted in calculation of wall movements in only one direction by ignoring the sign of the real variable. The same subroutine had worked satisfactorily under the old operating system. This spurious calculation resulted in unidirectional movement of the walls, increasing the level of residual interference with additional iterations showing no sign of convergence of wall shapes.

This limitation was overcome by defining the integer constant as a real number in the IFLEX subroutine. With this change, the adaptive wall software worked satisfactorily. The successful operation was demonstrated on a 13-inch chord NACA-0012 airfoil model at two angles of attack. Following this, another airfoil model has been tested successfully by the 0.3-m TCT staff over a range of Mach numbers and angles of attack. The observed limitation of the new operating system requires caution in developing new programs until the system is modified.

Improvements to software

During the course of the check-out program, a new procedure for setting the scaling factors for top and bottom walls was suggested. The new procedure provides a choice for choosing scaling factors either automatically or manually through the digital constants panel. This change eliminates the need for maintaining different programs for these tasks. Often, while testing under hard to adapt conditions, it is desirable to use the manual feature to set lower values of the scaling parameters to improve convergence. Mr. Eric Walberg implemented the new procedure in the adaptive wall software.

APPENDIX B

Isentropic Expansion of Sulfur Hexafluoride (SF₆)

The equation of state and the ideal constant-pressure heat capacity for SF₆ are given by^{12,13}

$$P = \frac{RT}{(V - b)} \sum_{i=2}^{i=5} \frac{a_i + h_i T + c_i \exp(-kT/T_c)}{(V - b)^i} \quad \text{B1}$$

$$C_p^o = A_0 + A_1 T + A_2 T^2 + A_3 T^3 + A_4 T^{-2} \quad \text{B2}$$

The various constants equations A1 and A2 are given by

$$b = 0.047812001$$

$$k = 6.8830220$$

$$T_c = 318.8$$

$$a_2 = -1.064506759 \times 10^6$$

$$a_3 = -1.284952625 \times 10^5$$

$$a_4 = -7.338851897 \times 10^3$$

$$a_5 = -3.25590376$$

$$h_2 = -1.170089157 \times 10^3$$

$$h_3 = -1.040549130 \times 10^2$$

$$h_4 = 0.0$$

$$h_5 = 7.271143381 \times 10^{-1}$$

$$c_2 = -5.067990044 \times 10^7$$

$$c_3 = 8.783983640 \times 10^6$$

$$c_4 = 0.0$$

$$c_5 = -2.048535876 \times 10^4$$

$$A_0 = -15748.49323$$

$$A_1 = 575.7699892$$

$$A_2 = -0.749044588$$

$$A_3 = 3.538653215 \times 10^{-4}$$

$$A_4 = -1.402388775 \times 10^8$$

For given values of pressure and temperature, the equation of state is solved to calculate the volume V. The constant pressure ideal heat capacity depends only on the temperature. The corresponding constant-volume ideal heat capacity C_v^o is given by

$$C_v^o = C_p^o - R \quad \text{B3}$$

where R is the universal gas constant.

The corresponding expressions for the heat capacities, C_p and C_v for the non-ideal behavior of the gas are given by

$$C_p - C_v = -T (\partial P / \partial T)^2 / (\partial P / \partial V) \quad B4$$

$$C_v = C_v^o + T (\partial^2 P / \partial T^2)_v dV \quad B5$$

For the real gas expansion from stagnation conditions at temperature T_t and volume V_t , to conditions at temperature T_1 and volume V_1 , the change in enthalpy (H) and entropy (S) are given by

$$\begin{aligned} H(T_t, V_t) - H(T_1, V_1) = & \int_{T_1}^{T_t} C_p^o dT - \int_{\infty}^{V_t} (P_t - RT_t/V_t) dV_t + T_t (\partial / \partial T_t) \int_{\infty}^{V_t} (P_t - RT_t/V_t) dV_t \\ & + \int_{\infty}^{V_1} (P_1 - RT_1/V_1) dV_1 - T_1 (\partial / \partial T_1) \int_{\infty}^{V_1} (P_1 - RT_1/V_1) dV_1 \\ & + (P_t V_t - RT_t) + (P_1 V_1 - RT_1) \end{aligned}$$

B6

$$\begin{aligned} S(T_t, V_t) - S(T_1, V_1) = & \int_{T_1}^{T_t} (C_p^o / T) dT - R \log(T_t / V_t) + (\partial / \partial T_t) \int_{\infty}^{V_t} (P_t - RT_t/V_t) dV_t \\ & - R \log(T_1 / V_1) + (\partial / \partial T_1) \int_{\infty}^{V_1} (P_1 - RT_1/V_1) dV_1 \end{aligned}$$

B7

The equations A6 and A7 are derived using the departure function technique defined by the difference in gas properties between the real and ideal states. For the particular case of isentropic expansion, the change in entropy between the initial and final conditions is zero. The temperature after isentropic expansion is determined by solving equations for state, heat capacity and the entropy. Because of the transcendental nature, the equations are solved iteratively. Knowing the change in enthalpy, the fluid velocity U after isentropic expansion is calculated from,

$$U = [2 (H(T_t, V_t) - H(T_1, V_1)) / W]^{1/2} \quad B8$$

where W is the molecular weight.

APPENDIX C

DIGITAL CONTROL PANEL SETTINGS

Parameter	Symbol	N ₂	SF ₆	Remarks
Analysis	IANAL	0	10	Airfoil Tests
		1	11	Empty TS Streamlining
		2	12	Re-analysis (Airfoil Tests)
		3	13	Development Streamlining
Scaling Factor	TWSF & BWSF	0.0	0.0	Automatic Scaling
				Iteration =1 0.80
				Iteration =2 0.70
				Iteration >=3 0.60
		>0.0	>0.0	Set Values For all Iterations >=1
Coupling Factor	TWCPLF BWCPLF	0.35	0.35	Recommended Value (Do not change)

APPENDIX D
SUMMARY OF ADAPTIVE WALL SOFTWARE MODIFICATIONS

Name	Status	Changes	Remarks
FLXWAS ⁺	E	Yes	Statements & calls related to IANAL parameter
INITWA ⁺	E	No	
STWALL	E	No	
WALCAL ⁺	E	No	
STAR ⁺	E	No	
WALDAT	E	Yes	Statements & calls related to IANAL parameter
WAS	E	Yes	Statements & calls related to IANAL parameter
SUME	E	Yes	Statements & calls related to IANAL parameter
OUT	E	Yes	Statements & calls related to IANAL parameter
IFLEX	E,M	No	Not documented. Further Modifications Nov '91.
ERROR ⁺	E	No	
SMOOTH	E	No	
FILESORT	E	No	Sorts array in ascending order
GETDATA	E	No	Gets wall data from Ref. Table
LIFT	E	No	
BLOCK	E	No	
OAPCM	E	No	Common Definition (System)
FLXCOM	E	No	Common Definition (Flexwall)
WASCOM	E	No	Common Definition (WAS)
FLXTYP	E	No	Type Declaration (Flexwall)
FWPTYP	E	No	Type Declaration (WASPAR)
WASTYP	E	No	Type Declaration (WAS)
FWPEQU	E	No	Equivalence (WASPAR)
FMASSIGN	E	No	Reference Table

continued.

APPENDIX D

SUMMARY OF ADAPTIVE WALL SOFTWARE MODIFICATIONS

Name	Status	Changes	Remarks
STARSF	New		Boundary-layer calculation for SF ₆ gas
SIMUL	New		Simulation of SF ₆ with N ₂ . (For initial checking)
SF6	New		Mach Number, Velocity and Density Calculation (SF ₆)
SISEN	New		Isentropic Expansion (SF ₆)
SVOL	New		Solves equation of State (SF ₆)
SSPHEAT	New		C _p , Specific heat at Constant Pressure Calculation. (SF ₆)
SINTCP	New		Calculates Integral of C _p from Temperature T ₁ to T _t (SF ₆)
SENRCP	New		Integral for Entropy change calculation (SF ₆)
SRCONS	New		Calculation of constants (SF ₆).

* Main Program; E: Existing; M: Modified

+ I/O changes only to compile on HP-Workstation.

Concluded.

Note: In addition to the programs listed in the table, the adaptive wall software contains/uses several other system calls and procedures for dedicated tasks.


```

C      ICODE          : CALCULATION CODE
C                      =0  REAL GAS CALCULATIONS
C                      =1  EXPANSION BASED ON STAGNATION GAMMA
C                      =2  EXPANSION BASED ON SPECIFIED GAMMA
C      IPRN           : PRINT PARAMETER
C                      =0, NO PRINT OUTOUT
C                      =1, OUTPUT FINAL PARAMETERS(ICODE=0)
C                      =2, LONG OUTPUT (FOR CHECK) (ICODE=0)
C      SPGAMA          : RATIO OF SPECIFIC HEATS (ONLY FOR ICODE=2)
C
C      RETURN PARAMETERS:
C      =====
C      EM(NPORTS)      : LOCAL MACH NUMBERS
C      DENS(NPORTS)     : DENSITY              (SLUGS/FT^3)
C      VELFPS(NPORTS)  : VELOCITY              (FT/SEC)
C      IERR(NPORTS)    : ERROR CODE
C                      =0  NORMAL RETURN
C                      =1  PSTAT TOO LOW FOR ISEN CALCULATIONS
C      /ISENX/          : PROPERTIES AFTER ISEN EXPANSION
C      /TOTL/           : PROPERTIES FOR STAG. CONDITIONS
C
C      SUBROUTINES CALLED:
C      =====
C      VOL:
C          RCONS
C          SPHEAT
C      ISEN:
C          VOL:
C              RCONS
C              SPHEAT
C          RCONS
C          ENRCP
C          INTCP
C      =====
C      COMMON /ISENX/ VEL, FMACH, FMASS, DYNPR, REY,
+          PSBYPT, T1BYTT, VTBYV1, DYNBYPT,
+          T1, V1, Z1, GAM1, AS1, DEN1
C      COMMON /TOTL/  ZT, GAMT, AST, DENT
C      DATA LO/@LO/
C      LO=6
C      DO 400 I=1, NPORTS
C      IERR(I)=0
C      PT=6894.7572D+00*PTOTAL
C      PS=6894.7572D+00*PSTAT(I)
C      TT=TTOTAL
C
C      IF(IPRN.NE.0) WRITE(LO,305)
305  FORMAT(/10X, 'STAGNATION CONDITIONS', /10X, '=====')
C
C      IF(I.EQ.1) CALL VOL(PT, TT, VT, ZT, GAMT, AST, DENT, IPRN)
C      PSCHEK=PS/PT
C      IF(PSCHEK.LT.0.1) GOTO 330
C
C      IF(IPRN.NE.0 .AND. ICODE.EQ.0) WRITE(LO,310)
C      IF(IPRN.NE.0 .AND. ICODE.EQ.1) WRITE(LO,311) GAMT
C      IF(IPRN.NE.0 .AND. ICODE.EQ.2) WRITE(LO,312) SPGAMA
310  FORMAT(/10X, 'ISENTROPIC EXPANSION (ICODE=0; REAL GAS):'
+      , /10X, '=====')
311  FORMAT(/10X, 'ISENTROPIC EXPANSION (ICODE=1; STAG GAMA=', F8.4, '))'
+      , /10X, '=====')

```

```

312 FORMAT(/10X,'ISENTROPIC EXPANSION (ICODE=2; SPEC GAMA=',F8.4,')'
+      ,/10X,'=====')
C
C
C   REAL GAS CALCULATIONS FOR EXPANSION
C   IF(ICODE.EQ.1 .OR. ICODE.EQ.2) GO TO 315
C   IF(ICODE.EQ.0) CALL ISEN(PT,TT,VT,PS,GAMT,IPRN)
C   GOTO 320
C
C   ISENTROPIC EXP BASED ON STAGNATION CONDITIONS
315 IF(ICODE.EQ.2) GOTO 318
G1=(GAMT-1.0)/2.0
G2=(GAMT-1.0)/GAMT
FMACH=SQRT( ( (PT/PS)**(G2) -1.0 )/G1 )
G3=1.0/(GAMT-1.0)
G =1.0 + G2*FMACH*FMACH
DEN1=DENT/(G**G3)
AS1 =AST /SQRT(G)
VEL =FMACH*AS1
GOTO 320
C
C   ISENTROPIC EXPANSION USING SPECIFIED GAMMA VALUE
318 G1=(SPGAMA-1.0)/2.0
G2=(SPGAMA-1.0)/SPGAMA
FMACH=SQRT( ( (PT/PS)**(G2) -1.0 )/G1 )
G3=1.0/(SPGAMA-1.0)
G =1.0 + G2*FMACH*FMACH
DEN1=DENT/(G**G3)
AS1 =AST /SQRT(G)
VEL =FMACH*AS1
C
C   STORE VALUES
320 EM(I)=FMACH
DENS(I)=DEN1/515.379D+00
VELFPS(I) =VEL/0.3048
GOTO 400
330 IERR(I)=1
400 CONTINUE
RETURN
END
C
SUBROUTINE ISEN(PT,TT,VT,PS,GAMT,IPRINT)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION AT(5),DAT(5),DDAT(5),A1(5),DA1(5),DDA1(5)
C
C   PURPOSE:
C   =====
C   TO CALCULATE ISENTROPIC EXPANSION FOR REAL GAS FROM
C   GIVEN STAGNATION PRESSURE & TEMPERATURE TO A SPECIFIED
C   EXPANSION PRESSURE.
C
C   ENTRY PARAMETERS:
C   =====
C   PT:  STAGNATION PRESSURE (N/M^2)
C   TT:  STAGNATION TEMPERATURE (K)
C   PS:  STATIC PRESSURE AFTER EXPANSION (N/M^2)
C   VT:  STAGNATION VOLUME
C   GAMT: RATIO OF SPECIFIC HEATS FOR PT & VT
C   IPRINT: OUTPUT PARAMETER
C           =0 NO OUTPUT TO DISPLAY
C           =1 RESULTS OUTPUT TO DISPLAY

```

```

C      RETURN PARAMETERS (IN /ISENX/)
C      =====
C      VEL      : VELOCITY (M/SEC)
C      FMACH    : MACH NUMBER
C      FMASS    : TEST-SECTION MASS FLOW (KGS/SEC)
C      DYNPR    : DYNAMIC PRESSURE (N/M^2)
C      REY      : REYNOLDS NO./METER
C      PSBYPT   : RATIO PSTATIC/PTOTAL
C      T1BYTT   : RATIO TSTATIC/TTOTAL
C      VTBYV1   : RATIO RHO-STATIC/RHO-TOTAL
C      DYNBYPT  : RATIO DYN-PR/PTOTAL
C      T1       : STATIC TEMPERATURE AFTER EXPANSION (K)
C      V1       : STATIC VOLUME AFTER EXPANSION (N/M^2)
C      Z1       : COMPRESSIBILITY FACTOR
C      GAM1     : RATIO OF SPECIFIC HEAT AFTER EXPANSION
C      AS1      : SPEED OF SOUND FOR STATIC CONDITIONS (M/SEC)
C      DEN1     : DENSITY (KG/M^3)
C
C      SUBROUTINES CALLED
C      =====
C      VOL:
C          RCONS
C          SPHEAT
C      RCONS:
C      ENRCP:
C      INTCP:
C
C      COMMON /ISENX/ VEL, FMACH, FMASS, DYNPR, REY,
+          PSBYPT, T1BYTT, VTBYV1, DYNBYPT,
+          T1, V1, Z1, GAM1, AS1, DEN1
C      LO=6
C      CALL RCONS(TT, AT, DAT, DDAT)
C      XT = 1.0D+00/(VT-0.047812001D+00)
C      ISENTROPIC EXPANSION
C      G1=(GAMT-1.0D+00)/GAMT
C      T1=TT*((PS/PT)**G1)
C      G3=2.0D+00/(GAMT-1.0D+00)
C      FM=(PT/PS)**G1 - 1.0D+00
C      FMT=DSQRT(G3*FM)
C      TLO=T1
C      TUP=0.999999999999D+00*TT
100  V1=8314.34D+00*T1/PS
C      IF(IPRINT.EQ.2) PRINT *, T1, V1
C      CALL ENRCP(TT, T1, S1)
150  S2 = 8314.34D+00*DLOG((TT*V1)/(VT*T1))
C      X1 = 1.0D+00/(V1-0.047812001D+00)
C
C      CALL RCONS(T1, A1, DA1, DDA1)
C
C      S3 =
+      -DAT(1)*DLOG(1.00D+00 + XT*0.047812001D+00)
+      +DA1(1)*DLOG(1.00D+00 + X1*0.047812001D+00)
+      -(DAT(2)*XT - DA1(2)*X1)
+      -(DAT(3)*XT*XT - DA1(3)*X1*X1)/2.0D+00
+      -(DAT(4)*XT*XT*XT - DA1(4)*X1*X1*X1)/3.0D+00
+      -(DAT(5)*XT*XT*XT*XT - DA1(5)*X1*X1*X1*X1)/4.0D+00
C      IF(IPRINT.EQ.2) PRINT *, 'S1, S2, S3'
C      IF(IPRINT.EQ.2) PRINT *, S1, S2, S3
C      G = S1 - S2 + S3

```

```

      DPV = DA1(5)*(X1**5.0D+00) + DA1(4)*(X1**4.0D+00)
      + DA1(3)*(X1**3.0D+00)
      + DA1(2)*(X1**2.0D+00) + DA1(1)*(X1)
      DGV = -DPV
      IF(IPRINT.EQ.2) PRINT *, DPV, DGV
      V2 = V1 - G/DGV
      IF(IPRINT.EQ.2) PRINT *, V1,V2
C      IF (DABS(V2-V1).LT.1.D-11) GOTO 200  change date 7/13/92
      IF (DABS(V2-V1).LT.1.D-11 .OR. V2.LT.VT) GOTO 200
      V1= V2
      GOTO 150
C
200 PS1= A1(5)*(X1**5.0D+00) + A1(4)*(X1**4.0D+00)
      + A1(3)*(X1**3.0D+00)
      + A1(2)*(X1**2.0D+00) + A1(1)*(X1)
      IF(IPRINT.EQ.2) PRINT *, PS1,PS
C
C      ACCURACY CHANGED 7/17/1992 TO 10PASCALS TO IMPROVE
C      CONVERGENCE AT LOW PRESSURES
C      IF(DABS(PS1-PS).LT.0.05D+00) GOTO 300
C      IF(DABS(PS1-PS).LT.10.0D+00) GOTO 300
C
      IF((PS-PS1).LT.0.0) GO TO 250
      TLO=T1
      T1 = (TLO+TUP)/2.0D+00
      GOTO 100
250 TUP=T1
      T1 = (TLO+TUP)/2.0D+00
      GOTO 100
300 CONTINUE
C
      CALL VOL(PS,T1,V1,Z1,GAM1,AS1,DEN1,IPRINT)
C      ENTHALPY CALCULATION
      CALL INTCP(TT,T1,S1)
      S2 = -AT(1)*DLOG(1.00D+00 + XT*0.047812001D+00)
      + -AT(2)*XT
      + -AT(3)*XT*XT/2.0D+00
      + -AT(4)*XT*XT*XT/3.0D+00
      + -AT(5)*XT*XT*XT*XT/4.0D+00
C      PRINT *, S1, S2
      S3 = -A1(1)*DLOG(1.00D+00 + X1*0.047812001D+00)
      + -A1(2)*X1
      + -A1(3)*X1*X1/2.0D+00
      + -A1(4)*X1*X1*X1/3.0D+00
      + -A1(5)*X1*X1*X1*X1/4.0D+00
C      PRINT *, S3
      S4 = -DAT(1)*DLOG(1.00D+00 + XT*0.047812001D+00)
      + -DAT(2)*XT
      + -DAT(3)*XT*XT/2.0D+00
      + -DAT(4)*XT*XT*XT/3.0D+00
      + -DAT(5)*XT*XT*XT*XT/4.0D+00
      S4 = TT*S4
C      PRINT *, S4
      S5 = -DA1(1)*DLOG(1.00D+00 + X1*0.047812001D+00)
      + -DA1(2)*X1
      + -DA1(3)*X1*X1/2.0D+00
      + -DA1(4)*X1*X1*X1/3.0D+00
      + -DA1(5)*X1*X1*X1*X1/4.0D+00
      S5 = T1*S5
C      PRINT *, S5

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S6 = PT*VT - PS*V1 + 8314.34D+00*(T1 -TT)
C   PRINT *, S6
DH = S1 - S2 + S3 + S4 - S5 + S6
IF(IPRINT.EQ.2) PRINT *, DH
VEL= DSQRT(2.0D+00*DH/146.054D+00)
G1=(GAM1-1.0D+00)/GAM1
G3=2.0D+00/(GAM1-1.0D+00)
FM=(PT/PS)**G1 - 1.0D+00
FM1=DSQRT(G3*FM)
FMACH= VEL/AS1
FMASS=VEL*DEN1*0.1090D+00
DYNPR=0.5D+00*DEN1*VEL*VEL
REY  =DEN1*VEL/(T1*5.59D-08 - 8.0D-07)
PSBYPT=PS/PT
T1BYTT=T1/TT
VTBYV1=VT/V1
DYNBYPT=DYNPR/PT
IF(IPRINT.EQ.1 .OR. IPRINT.EQ.2) WRITE(LO,310)
+VEL,FMACH,FMASS,DEN1,DYNPR,REY,PSBYPT,T1BYTT,VTBYV1,DYNBYPT
310 FORMAT(/10X,'VELOCITY (M/SEC) ..... =',F20.6,
+        /10X,'MACH NUMBER ..... =',F20.6,
+        /10X,'TEST-SECTION MASS FLOW (KGS/SEC) ..... =',F20.6,
+        /10X,'DENSITY, KG/M^3 ..... =',F20.6,
+        /10X,'DYNAMIC PRESSURE (N/M^2) ..... =',F20.6,
+        /10X,'REYNOLDS NO./METER ..... =',E20.6,
+        /10X,'RATIO PSTATIC/PTOTAL ..... =',F20.6,
+        /10X,'RATIO TSTATIC/TTOTAL ..... =',F20.6,
+        /10X,'RATIO RHO-STATIC/RHO-TOTAL ..... =',F20.6,
+        /10X,'RATIO DYN-PR/PTOTAL ..... =',F20.6)
C
IF(IPRINT.EQ.2) PRINT *, 'S1,S2,S3,S4,S5,S6,DH/146.054D+00'
IF(IPRINT.EQ.2) PRINT *, 'S1,S2,S3,S4,S5,S6,DH/146.054D+00'
IF(IPRINT.EQ.2) PRINT *, 'VEL,FMACH,FMT,FM1'
IF(IPRINT.EQ.2) PRINT *, 'VEL,FMACH,FMT,FM1'
RETURN
END
SUBROUTINE VOL(P,T,V,Z,GAM,AS,DEN,IPRINT)
C   P: IN PASCALS(N/M**2); T: IN KELVIN; V: M**3/KMOLE (OUTPUT)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(5),DA(5),DDA(5)
LO=6
CALL RCONS(T,A,DA,DDA)
X = P/(8314.34D+00*T)
100 F = A(5)*(X**5.0D+00) + A(4)*(X**4.0D+00) + A(3)*(X**3.0D+00)
+      +A(2)*(X**2.0D+00) + A(1)*(X) - P
FD= 5.0D+00*A(5)*(X**4.0D+00) + 4.0D+00*A(4)*(X**3.0D+00)
+      +3.0D+00*A(3)*(X**2.0D+00) + 2.0D+00*A(2)*X + A(1)
X1= X - F/FD
IF (DABS(X1-X).LE. 1.0D-10) GOTO 200
X = X1
GOTO 100
200 CONTINUE
C
C   CALCULATE VOLUME & COMPRESSIBILITY FACTOR
V = 0.047812001D+00 + (1.0D+00/X)
Z = (P*V)/(8314.34D+00 *T)
C
C   CALCULATE CP-CV
DPV = -5.0D+00*A(5)*(X**6.0D+00) - 4.0D+00*A(4)*(X**5.0D+00)
+      -3.0D+00*A(3)*(X**4.0D+00)
+      -2.0D+00*A(2)*(X**3.0D+00) - A(1)*(X**2.0D+00)

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      DPT = DA(5)*(X**5.0D+00) + DA(4)*(X**4.0D+00)
+      +DA(3)*(X**3.0D+00)
+      +DA(2)*(X**2.0D+00) + DA(1)*(X)
      CPMCV= -T*(DPT*DPT)/DPV

C
C      DINT IS INTEGRAL OF DDPDTT W.R.T V
      DINT = -(DDA(5)/4.0D+00)*(X**4.0D+00)
+      -(DDA(3)/2.0D+00)*(X**2.0D+00)
+      -(DDA(2)/1.0D+00)*(X)
      CALL SPHEAT(T,CP0)
      CV0 = CP0 - 8314.34D+00
      CV = CV0 + T*DINT
      IF(IPRINT.EQ.2) PRINT *, CP0,CV0
      GAM = 1.0D+00 + (CPMCV/CV)
      CP = CPMCV + CV

C
C      SPEED OF SOUND
      AS = DSQRT(-GAM*V*V*DPV/146.054D+00)
      DEN = 146.054D+00/V

C
      IF(IPRINT.EQ.1 .OR. IPRINT.EQ.2) WRITE(LO,300)
+P,T,V,DEN,Z,CP0,CV0,CPMCV,CP,CV,GAM,AS
300 FORMAT( 10X,'P, NEWTON/M^2 ..... =',F20.6,
+      /10X,'T, TEMPERATURE, K ..... =',F20.6,
+      /10X,'V, VOLUME M^3/KMOLE ..... =',F20.6,
+      /10X,'DENSITY, KG/M^3 ..... =',F20.6,
+      /10X,'Z, COMPRESSIBILITY FACTOR ..... =',F20.6,
+      /10X,'CP0, CONS PR IDEAL HEAT CAP. J/KMOLE.K ..... =',F20.6,
+      /10X,'CV0, CONS VOL IDEAL HEAT CAP. J/KMOLE.K ..... =',F20.6,
+      /10X,'CP-CV, J/KMOLE.K ..... =',F20.6,
+      /10X,'CP, CONS PR HEAT CAP. J/KMOLE.K ..... =',F20.6,
+      /10X,'CV, CONS VOL HEAT CAP. J/KMOLE.K ..... =',F20.6,
+      /10X,'GAMMA (RATIO CP/CV)..... =',F20.6,
+      /10X,'SOUND SPEED, METERS/SEC..... =',F20.6)
      RETURN
      END

C
      SUBROUTINE SPHEAT(T,CP)
      IMPLICIT REAL*8 (A-H,O-Z)

C
C      PURPOSE: TO CALCULATE CONSTANT PRESSURE IDEAL HEAT CAPACITY
C      ENTRY : T, TEMPERATURE (K)
C      RETURN : CP, SPECIFIC HEAT J/(KMOLE.K)
C
      CP = -15748.49323D+00 + 575.7699892D+00 * T
+      - 0.749044588D+00 *(T**2.0D+00)
+      + 3.538653215D-04 *(T**3.0D+00)
+      - 1.402388775D+08 *(T**(-2.0D+00))
      RETURN
      END

C
      SUBROUTINE INTCP(TT,T1,S1)
      IMPLICIT REAL*8 (A-H,O-Z)
      S1 = -15748.49323D+00*(TT-T1)
+      +575.7699892D+00*(TT*TT-T1*T1)/2.0D+00
+      -0.749044588D+00*(TT*TT*TT-T1*T1*T1)/3.0D+00
+      +3.538653215D-04*(TT*TT*TT*TT-T1*T1*T1*T1)/4.0D+00
+      -1.402388775D+08*(-1.0D+00/TT +1.0D+00/T1)
      RETURN
      END

```

C

```

SUBROUTINE ENRCP(TT,T1,S1)
IMPLICIT REAL*8 (A-H,O-Z)
S1 = - 15748.49323D+00*DLOG(TT/T1)
+   + 575.7699892D+00*(TT -T1)
+   - 0.749044588D+00*(TT*TT -T1*T1)/2.0D+00
+   + 3.538653215D-04*(TT*TT*TT -T1*T1*T1)/3.0D+00
+   + 1.402388775D+08*(0.5D+00/TT**2.0D+00)
+   - 1.402388775D+08*(0.5D+00/T1**2.0D+00)

```

C

```

PRINT *, TT, T1, S1
RETURN
END

```

C

```

SUBROUTINE RCONS(T,A,DA,DDA)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(5),DA(5),DDA(5)
EXPCON=DEXP(-6.8830220D+00*T/318.80D+00)
A(5)=-3.25599376D+00 +7.271143381D-01*T -2.048535876D+04*EXPCON
A(4)=-7.338851897D+03
A(3)= 1.284952625D+05 -1.04054913D+02 *T +8.78398364D+06 *EXPCON
A(2)=-1.064506759D+06 +1.170089157D+03*T -5.067990044D+07*EXPCON
A(1)= 8314.34D+00 *T

```

C

```

DEXPCO=(-6.8830220D+00/318.80D+00)*EXPCON
DA(5) = 7.271143381D-01 - 2.048535876D+04*DEXPCO
DA(4) = 0.0D+0
DA(3) =-1.04054913D+02 + 8.78398364D+06 *DEXPCO
DA(2) = 1.170089157D+03 - 5.067990044D+07*DEXPCO
DA(1) = 8314.34D+00

```

C

```

DDEXPC= ((-6.8830220D+00/318.80D+00)**2.0D+00)*EXPCON
DDA(5)= - 2.048535876D+04*DDEXPC
DDA(4)= 0.0D+0
DDA(3)= 8.78398364D+06 *DDEXPC
DDA(2)= - 5.067990044D+07*DDEXPC
DDA(1)= 0.0D+00
RETURN
END

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